

Greenland Ice Sheet: Increased coastal thinning

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[1] Repeated laser-altimeter surveys and modelled snowfall/summer melt show average ice loss from Greenland between 1997 and 2003 was $80 \pm 12 \text{ km}^3 \text{ yr}^{-1}$, compared to about $60 \text{ km}^3 \text{ yr}^{-1}$ for 1993/4–1998/9. Half of the increase was from higher summer melting, with the rest caused by velocities of some glaciers exceeding those needed to balance upstream snow accumulation. Velocities of one large glacier almost doubled between 1997 and 2003, resulting in net loss from its drainage basin by about 20 km^3 of ice between 2002 and 2003. **INDEX TERMS:** 1640 Global Change: Remote sensing; 1863 Hydrology: Snow and ice (1827); 4556 Oceanography: Physical: Sea level variations. **Citation:** Krabill, W., et al. (2004), Greenland Ice Sheet: Increased coastal thinning, *Geophys. Res. Lett.*, 31, L24402, doi:10.1029/2004GL021533.

1. Introduction

[2] Recent observations show central parts of the Greenland Ice Sheet (GrIS) to be in balance, but with enough thinning at lower elevations to raise sea level by about 0.13 mm yr^{-1} . Results were from estimates of surface-elevation change inferred from laser-altimeter surveys with NASA's Airborne Topographic Mapper (ATM) in 1993/94 repeated in 1998/99 [Krabill et al., 2000], and volume-budget comparison of snow accumulation with ice discharge [Thomas et al., 2001]. Although the aircraft measurements refer only to conditions during the interim between surveys, they agree closely with the volume-budget estimate indicating that the ice sheet above 2000-m elevation, taken as a whole, has been almost exactly in balance for the past few decades [Thomas et al., 2001].

[3] Low-elevation results were based only on aircraft measurements, primarily along outlet glaciers. These show widespread thinning at rates generally exceeding those expected from increased melting during recent warmer summers [Abdalati et al., 2001]. Consequently, part of the thinning was dynamic, possibly initiated by changes associated with the warming. If so, this calls into question

current prediction of sea-level rise in a warmer climate [Church et al., 2001] that includes only a very small dynamic glacier response. Here, we report results from aircraft surveys made since 1999 over many of the coastal regions surveyed earlier, showing overall increase in thinning rates consistent with more surface melting during warmer summers plus a substantial increase in dynamic thinning.

2. Methods

[4] Our estimates of surface-elevation change rates (dh/dt) are from comparison of ATM measurements, with elevation accuracy of $\sim 10 \text{ cm}$ for flight lines of several hundred km [Krabill et al., 2002]. Recent surveys focussed on coastal regions in order to investigate areas undergoing most rapid changes so overall coverage is sparser than for 1993/4 and 1998/9 surveys, with higher-elevation coverage confined to the northern half of the ice sheet. At lower elevations, a strong seasonal elevation change is associated with brief periods of intense summer melting followed by slow thickening from snow accumulation and seaward ice motion. Consequently, comparison is best between surveys made during the same season. Most surveys were in May (exceptions were June/July 1993 and 1998), so we show results obtained by comparing recent data with surveys from 1997 and later, but not 1998. Results (Figure 1) show small changes in dh/dt for high-elevation regions compared to earlier surveys, but a general trend towards thinning, possibly resulting from interannual variability in snow-accumulation rates [Davis et al., 2001].

[5] At lower elevations, thinning rates increased in most coastal regions, except in the SE. Here, the ice thickened by more than 1 m between May 2002 and May 2003, compared to thinning averaging $10\text{--}40 \text{ cm yr}^{-1}$ between 1993 and 1998 (Figure 2). This can be explained only by an approximate doubling in local precipitation in an area where accumulation rates are the highest in Greenland due to prevailing easterly winds, frequent cyclogenesis in and near Fram Strait, relatively low latitude, high moisture availability from an often warm ocean, and most importantly, orographic enhancement against steep coastal slopes. Precipitation commonly exceeds $1\text{--}2 \text{ m of water yr}^{-1}$ in the SE, mostly in winter [Cappelen et al., 2001]. Unusually high accumulation in SE Greenland in 2002–3 is supported by an accumulation model driven by ECMWF (mainly ERA-40) analyses [Hanna et al., 2001, 2002; also Observed and modeled Greenland Ice Sheet snow accumulation, 1958–2003, and links with regional climate forcing, submitted to *Journal of Climate*, 2004, hereinafter referred to as Hanna et al., submitted manuscript, 2004]. Modelled snowfall, corrected for evaporation/sublimation, for the area

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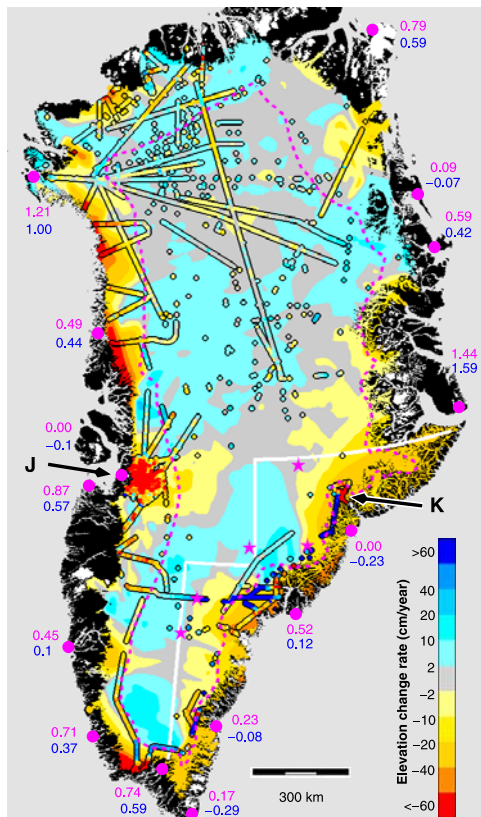


Figure 1. Rates of elevation change along ATM flight lines during 1997–2003, superimposed on a map of elevation-change rates resulting from the 1993/94 and 1998/99 surveys [Krabill *et al.*, 2000]. Differences between average summer temperatures (June/July/August), and those for 1961–90, are listed at coastal weather stations, for 1997–2002 (upper) and 1993–99 (lower). The region outlined in the southeast consistently thinned until 2001, and then thickened substantially between May 2001 and May 2003. “J” and “K” show Jakobshavn Isbrae and Kangerdlugssuaq Glaciers. The broken line indicates the 2000 meter contour. Ice cores discussed in the text are marked by stars.

shown in Figure 1 was 1.21 m of water for June 2002–May 2003, or 75% (3.5 standard deviations) above mean annual June–May (1958/9–2002/3) accumulation of 0.69 m. This is unprecedented in at least the last 46 years of available analysis/model data, and in more than 100 years, based on data from nearby ice cores shown in Figure 1 (J. R. McConnell, personal communication, April 2004). The 0.5 m water equivalent of additional accumulation represents about 1.5 m depth of snow with density $\sim 330 \text{ kg m}^{-3}$, in good agreement with observed thickening during the same period.

[6] Unusually high 2002/03 accumulation was almost certainly due to exceptionally high winter cyclonic activity over SE Greenland; mean sea level pressure charts (NCEP Operational dataset) show -5 to -10 mb anomalies over S Greenland from November 2002 to March 2003. The synoptic pattern over the northern North Atlantic was also exceptional based on records since at least 1990, and local snowfall should return to lower, near-‘normal’ values

(Hanna *et al.*, submitted manuscript, 2004). However, enhancement of SE Greenland precipitation and more inter-annual variability with greater frequency of highly anomalous snowfall, may be hallmarks of ongoing climatic change [Church *et al.*, 2001; Huybrechts *et al.*, 2004].

[7] Despite extremely high 2002–03 snowfall in the SE, Figure 1 shows enhanced thinning of most coastal regions, consistent with recent summer temperatures considerably higher than for 1993–98, which were already warmer than the longer-term 1961–90 averages (Figure 1). We estimated total ice-sheet melt losses (runoff) during 1993–98 and 1997–2003, by comparing ECMWF-based estimates of runoff, corrected for variable snowfall and for water retained after percolation into surface snow [Huybrechts *et al.*, 2004; Janssens and Huybrechts, 2000], with equivalent values for 1961–90. A monthly version of a degree-day runoff/retention model [Huybrechts *et al.*, 2004] was used, with surface air temperature and precipitation/evaporation from ECMWF analyses, to calculate monthly runoff on a $5 \times 5 \text{ km}$ grid. Surface air temperatures, corrected for orography errors in the ECMWF model, agree within $<1^\circ\text{C}$ with weather station data. For 1961–90, runoff resulting from this approach was equivalent to $\sim 305 \pm 33 \text{ km}^3 \text{ yr}^{-1}$ of ice, very close to the average ($315 \text{ km}^3 \text{ yr}^{-1}$) of several other model results [Church *et al.*, 2001; Huybrechts *et al.*, 2004]. Resulting estimates of net ice loss associated with melting/snowfall anomalies were $35 \pm 5 \text{ km}^3 \text{ yr}^{-1}$ for 1993–98, and $46 \pm 7 \text{ km}^3 \text{ yr}^{-1}$ for 1997–2003. Although these estimates are approximate, they indicate that melt losses increased over recent years.

[8] The 1993–98 excess runoff is about two thirds of the $51 \text{ km}^3 \text{ yr}^{-1}$ ice loss estimated by interpolation between measurements of elevation changes from repeat laser-altimeter surveys during this period [Krabill *et al.*, 2000], but not including thinning rates $>1 \text{ m yr}^{-1}$ that were unlikely to be representative of less active surrounding ice. Instead, values were interpolated between measured thinning $<1 \text{ m yr}^{-1}$ and near-coastal thinning calculated as that caused only by anomalous melting consistent with warmer summers [Krabill *et al.*, 2000; Abdalati *et al.*, 2001].

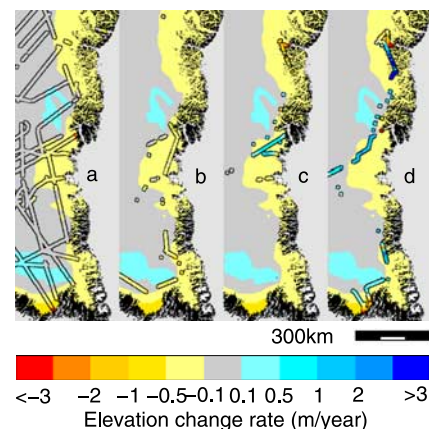


Figure 2. Rates of surface-elevation change (m yr^{-1}) along the SE side of the ice sheet: (a) 1993–98; (b) 1997–2001; (c) 2001–02; (d) 2002–03. Background colors refer to 1993–98, and those along flight lines refer to the relevant time interval. Note change in color scale from Figure 1.